Chesapeake Bay Program

Technology Transfer Report

Response of the Chesapeake Bay Water Quality Model to Loading Scenarios

Prepared by the Modeling Subcommittee
of the
Chesapeake Bay Program

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Technical Analysis of Response of Chesapeake Bay Water Quality Model to Loading Scenarios

A Report of the
Modeling Subcommittee
Chesapeake Bay Program Office
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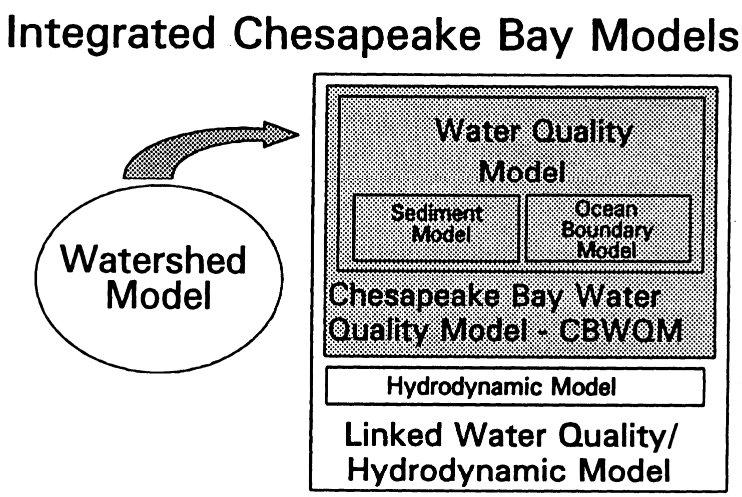
PREFACE

In 1983, the Chesapeake Bay Program identified excess nutrients, or eutrophication, as the primary reason for water quality decline in the Chesapeake[1]. To quantify the nutrients contributing to eutrophication and the nutrient reductions necessary to restore Chesapeake Bay resources, several water quality models have been developed and applied.

The first model application was the Watershed Model. The first phase of that model, completed in 1982, documented the magnitude and source of the point and nonpoint nutrient loads to the Bay for wet, dry, and average hydrology years[1].

To examine the impact of nutrient loads on the mainstem Bay, a steady state water quality model of the Bay was completed in 1987. Using simplified loading estimates and simulation procedures, this model calculated the average or steady state summer (June - September) conditions in the mainstem Bay . Results from the steady-state model indicated that a 40% reduction in nutrient loads would eliminate anoxia (dissolved oxygen concentrations less than 1.0 mg/l) in the mainstem.

To confirm the estimates of anoxia reduction, and to refine estimates of the improvements in Bay water quality in response to nutrient load reductions, work began on an integrated set of Chesapeake Bay models in 1987 (shown below). The linked watershed, hydrodynamic, water quality, and sediment models were completed in 1992. This report documents the findings from the application of these integrated models to evaluating the technical aspects of various load reduction scenarios.



WATERSHED MODEL

The Watershed Model was updated to provide greater detail of atmospheric and agricultural sources[2]. This model was used to 1) determine the distribution of the point and nonpoint source loads and the controllable and uncontrollable portions of the loads; 2) determine the quantity of loads reduced under different management actions; 3) determine the nutrient loads to the Bay under different Clean Air Act scenarios; and 4) quantify the loads under future (year 2000 conditions). These loads were used as input conditions for the Chesapeake Bay Water Quality Model.

CHESAPEAKE BAY WATER QUALITY MODEL (CBWQM)

The CBWQM is a time variable, three dimensional water quality model coupled with a model of sediment processes. The sediment model provides simulation of sediment nutrient sources and sinks. An ocean boundary submodel simulates the expected coastal input of loads under different nutrient management conditions. The CBWQM is driven by a hydrodynamic model simulating the hourly movement of Bay waters over the three year (1984 - 1986) simulation period. The details of model development, structure, calibration, and sensitivity are given in separate reports[3,4,5].

The work described in this report is by no means complete. Scenarios have been applied to develop the tributary loading allocations of a 40% reduction of controllable nitrogen and phosphorus and to annually track the loads to compare annual reductions with the year 2000 goal.

Further model refinements are now under way. These refinements will examine the relationship among air deposition, water quality and key living resource areas including SAV, benthos, and phytoplankton/zooplankton. The refined model analysis of air deposition, and water quality/living resource interaction will be completed in 1997.

ENDNOTES

1. M.E. Gillelan et al., 1983. Chesapeake Bay: A Framework for Action U.S. EPA Chesapeake Bay Program. Annapolis, MD.

2. A.S. Donigian et al., 1991. Watershed Model Application to calculate Bay Nutrient Loads: Phase II Findings and Recommendations U.S. EPA Chesapeake Bay Program. Annapolis, MD

3. C.F. Cerco and T. Cole, 1993. Application of the Three-Dimensional Eutrophication Model CE-QUAL-ICM to Chesapeake Bay U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

4. D.M. Di Toto and J.J. Fitzpatrick, 1993. Chesapeake Bay Sediment Flux Model U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS

5. B.H. Johnson et al., 1991. Users Guide for a Three-Dimensional Numerical Hydrodynamic, Salinity, and Temperature Model of Chesapeake Bay U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

TECHNICAL SUMMARY

INTRODUCTION

A modeling framework was constructed for the Chesapeake Bay system to provide a credible basis to assist the decision-making process and to further the understanding of Bay water quality processes and the sensitivity of such processes to external nutrient loading. The modeling structure consists of a Watershed Model to generate nutrient loads from the Bay sub-basins; a three-dimensional, time variable hydrodynamic model; and a three-dimensional, time variable model of water quality coupled to a model of sediment chemistry.

Extensive calibration analyses of the entire modeling structure was conducted using data collected primarily during a three year period from 1984-1986. The Chesapeake Bay Program Modeling Subcommittee completed its initial review of the Chesapeake Bay Water Quality Model (CBWQM) calibration in May 1991 and concluded the model could provide useful information to the Bay community, especially with respect to dissolved oxygen problems in the deep water of the main Bay. Final calibration of the CBWQM was completed in January 1992.

After completion of the model calibration, the models were used to address management issues such as: (1) What impact do reductions or increases in nutrient loads from point and nonpoint sources delivered by the Bay's major tributaries have on Chesapeake's water quality? and (2) How much of the nutrient loads to the Bay is natural and how much is related to man-made sources, and to what extent can loads be controlled?

The CBWQM provides projections of the expected water quality responses (including dissolved oxygen concentrations) in the main Bay under a variety of proposed management scenarios. The purposes of this report are therefore to (a) document the results of a full set of loading scenario computations, (b) analyze the scenario results across different loading conditions and (c) interpret the results in the light of the sensitivity of the Bay model to various loading conditions.

A total of 21 scenarios were run for this work and a summary description of the 11 scenarios that formed the basis for the analysis herein is given in the Table below.

Scenario Number	Scenario Tag	Scenario Description
1	BASE	1984-1986 Conditions
2	40% CONT	40% Reduction of controllable load ("Agreement" states only)
3	40% +CAA	Scenario #2 + Clean Air Act atmospheric reductions
4	40%CAA+BASIN	40% + CAA for entire basin
5	LOT	Limit of technology (LOT) for nutrient reductions
6	LOT -UPPER	Limit of technology for "Upper Bay" only, others at BASE
7	LOT - MID	Limit of technology for "Middle Bay" only, others at BASE
8	LOT - LOWER	Limit of technology for "Lower Bay" only, others at BASE
10	LOT - N ONLY	LOT for nitrogen only, phosphorus as incidental by N reduction
11	LOT - P ONLY	LOT for phosphorus only, nitrogen as incidental by P reduction
16	90% RED	90% reduction in total N & P loading from BASE

SCENARIO NUTRIENT LOADS

This report is focused on the response of the main Bay to various nutrient loading scenarios. The "external" loads are comprised of (1) fall line watershed loading, (2) below fall line watershed load, (3) point source loads, (4) atmospheric loads direct to the water surface of the Bay, and (5) ocean loading. The "internal" loadings from tidal tributaries to the Bay are calculated by the CBWQM and are given at the interface of the tributary with the main Bay. Fall line loadings and below fall line loadings are calculated from the Watershed Model (WSM). Point source loads were obtained from inventories. Atmospheric loads were estimated based on available data, and ocean boundary loads were estimated using shelf nutrient data and a simple exchange model at the mouth of the Bay.

The three principal reference loadings that established the extent of feasible reductions, are:

1. Base Case Load,
2. Controllable Load, and
3. Limit of Technology (LOT) Load.

a. Base Case. The Base Case loading represents the 1984 -1986 loading as a reference time period. This is the same period as used for the calibration of the CBWQM.

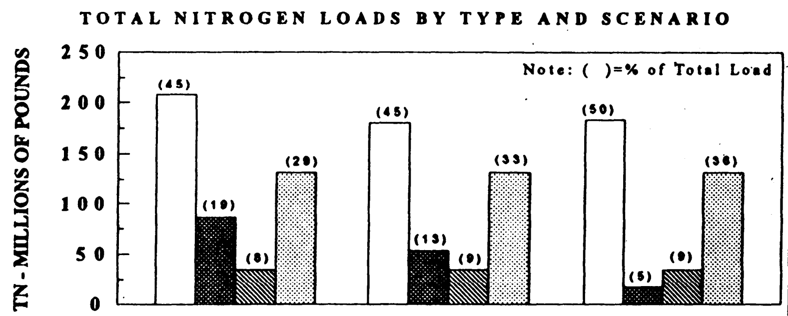
b. Controllable Load. Controllable loads are defined as the difference between Base Case loads and a WSM run using an all forested basin (excluding NY, WV & DE) with no point sources. 40% Controllable loads are those agreed to in the Bay agreements.

c. LOT Load. Limit of Technology loads for Non-Point Source (NPS) inputs were determined by evaluation of Best Management Practices (BMP) and implemented in the WSM. Point source (PS) LOT loads were assumed as follows: 3.0 mg/L for TN, 0.075 mg/L for TP, and 1.0 mg/L for BOD.

In order to represent year to year variation in hydrology, the scenario runs were conducted over a ten year period with flows representative of the interval from 1979 to 1988. Wet, dry and average years during this period were assigned the 1984, 1985 and 1986 hydrologies, respectively. The total river flows to the Bay for 1984 to 1986 are 487,300 cfs (13,800 m^3/s), 459,100 cfs (13,000 m^3/s), and 476,700 cfs (13,500 m^3/s), respectively. The CBWQM was run for these ten years in sequence and the final five years were output. In this report, the emphasis is on year #9, the average hydrologic year.

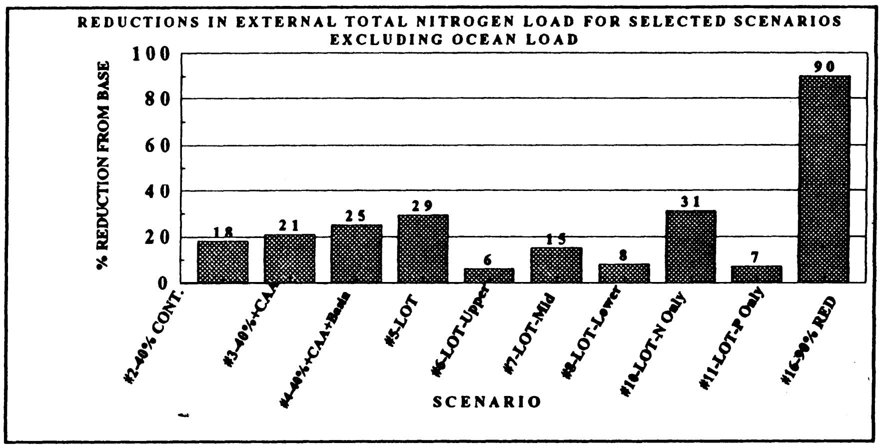
TOTAL NITROGEN LOADS

The Figure below shows the total annual nitrogen (TN) loads used for three of the principal scenarios: Base Case, 40% Controllable and the Limit of Technology (LOT). Base and LOT runs provide an approximate bounding of the feasible range of load reductions. As shown in this Figure, the major source of nitrogen is from the nonpoint sources making up more than 45% of the total for all three scenarios. The point sources decline from 19% of total at Base to 5% at LOT illustrating the greater possible reduction of point source loading relative to nonpoint source reduction. Atmospheric loading directly to the tidal waters is about 9% of total. Ocean loading of TN is a significant component of the total load to the Bay and is estimated to range from 29% to 36% of the TN loading for Base to LOT.



	#1-Base	#2-40% Cont	#5 LOT
NPS	207.5	180.4	183.0
PS	86.8	53.4	17.0
ATMOS.	34.6	34.6	34.6
OCEAN	131.8	131.8	131.8
TOTAL	460.7	400.2	366.4

The Figure below indicates the percent reduction of external TN loading (excluding ocean input) from the Base Case for selected scenarios. The increase in % reduction across the variations of the 40% Controllable (#2) through scenario #4 can be noted. Clean Air Act controls (CAA) on a basin-wide scale and including the non-basin states increase the percent reduction from 18% to 25%. It can also be seen that scenario #4 is approaching the LOT scenario #5. The LOT-Mid (#7) run removes almost as much TN as the 40% Controllable case.

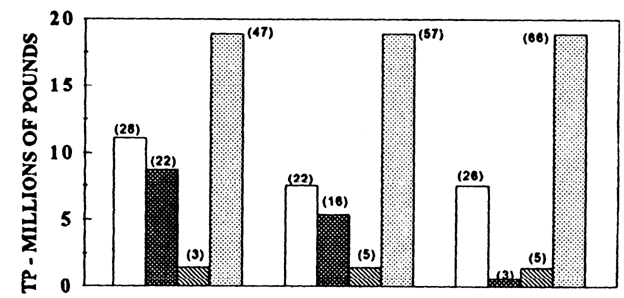


The relative reduction of TN loading due to point and nonpoint sources indicates that the point source loading is reduced considerably more than the nonpoint loading in the LOT scenario. In LOT, the point source loading is reduced about 85% from Base case while the nonpoint source loading is reduced 14-23% from Base. This is a reflection of the relative technological difficulty in reducing nonpoint TN loading as opposed to point TN inputs. It should be noted that location of such reductions is also important. The Upper Bay region is dominated by the nonpoint input of the Susquehanna River so that the contribution from point sources in that region is small while the middle Bay region is responsible for about 50% of the load reductions (Scenario #5 vs. #7).

TOTAL PHOSPHORUS LOADS

The accompanying Figure shows an important difference between TP and TN sources. As shown, the ocean loading of TP dominates the loading inputs accounting for as much as 66% of the TP load at the LOT scenario. It can also be noted that the nonpoint and point source loading are closer in magnitude than for TN, but for LOT the nonpoint load is about the same as for the 40% Controllable case. This is a reflection of the fact that most of the TP is considered controllable.

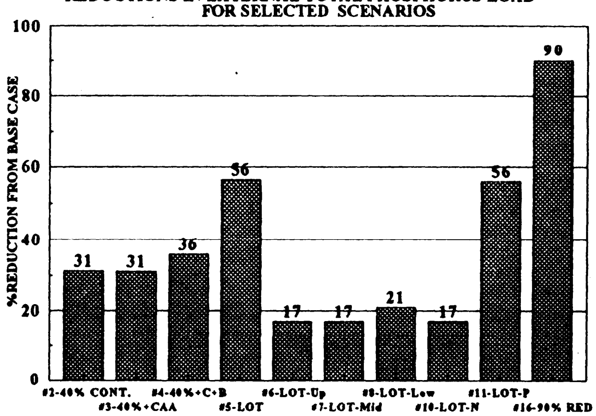
TOTAL PHOSPHORUS LOADS BY TYPE AND SCENARIO



	#1-Base	#2-40% Cont	#5 LOT
NPS	11.1	7.5	7.5
PS	8.8	5.4	0.6
ATMOS.	1.5	1.5	1.5
OCEAN	18.9	18.9	18.9
TOTAL	40.3	33.3	28.5

The percent reduction of TP from Base for a series of scenarios is given in the Figure to the left. The reductions are higher than for TN reflecting the greater technological control for TP over TN. For LOT, a 56% reduction is calculated although it should be recognized that if the ocean load were included, the net percent reduction of TP for LOT due to all loads drops to 29%.

REDUCTIONS IN EXTERNAL TOTAL PHOSPHORUS LOAD FOR SELECTED SCENARIOS



The following principal conclusions are drawn from this analysis of the TN and TP loads.

1. The upper limit of overall total nitrogen reduction from the base case is from about 20 - 30% of the total input load (excluding input from the ocean), with PS being more controllable than NPS.

2. The upper limit of overall total phosphorus reduction from the Base case is from about 30-55% of the total input load (excluding input from the ocean).

3. The calculated ocean nutrient input load (which is independent of scenario) is estimated to contribute about 30-35% of the total input nitrogen load and about 45-65% of the total input phosphorus load.

4. Deposition of atmospheric nitrogen directly to the Bay waters is about 10% of the Base case loading.

5. 40% reduction of controllable nitrogen for nonpoint sources is approximately equal to the Limit of Technology reduction of nitrogen nonpoint sources.

6. The application of LOT results in significantly larger percentage reductions in point source nutrient loadings to the Bay than nonpoint source loadings.

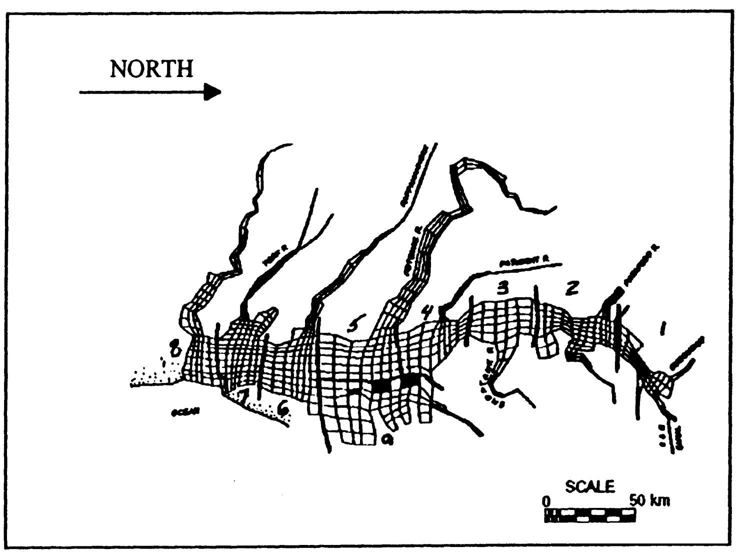
7. The loading to the Upper Bay is primarily from the Susquehanna River while the remainder of the Bay accounts for more than 50% of the load reductions.

CBWQM RESPONSE - GENERAL CONSIDERATIONS

Since model output for all state variables, time and locations is voluminous, some averaging of model results over time and space is necessary. Although the CBWQM calculates state variable concentrations at a time scale of hours, such calculations are for computational stability only. Input information is provided on a week to week basis and the kinetics that are incorporated in the model are representative of longer time behavior. The model is considered to represent processes on a time scale of months, seasons and longer. Therefore, some of the model output results were averaged over months while other results were averaged over seasons according to the Table below.

TEMPORAL PERIODS USED IN AVERAGING MODEL OUTPUT

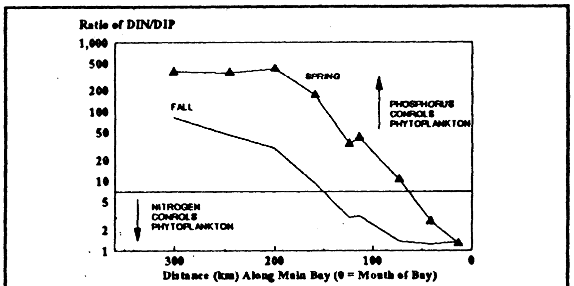
SEASON	DESCRIPTION	JULIAN DAY	APPROX. MONTHS
I	"Winter"	0 - 60	Jan.- Feb.
II	"Spring"	61 - 150	Mar. - May
III	"Summer"	151 - 270	June - Sept.
IV	"Fall"	271 - 365	Oct. - Dec.



The Bay spatial grid scale horizontally is about 10 km by 5 km by 1.7m and includes from two to fifteen cells in the vertical direction for a total of 4029 cells. Two sediment segments (aerobic and anaerobic) are incorporated under the water column segments. Again, in order to provide tractable output, water column model results are averaged spatially according to the zones indicated in the Figure below.

NUTRIENT, PHYTOPLANKTON, CARBON & SOD RESPONSE

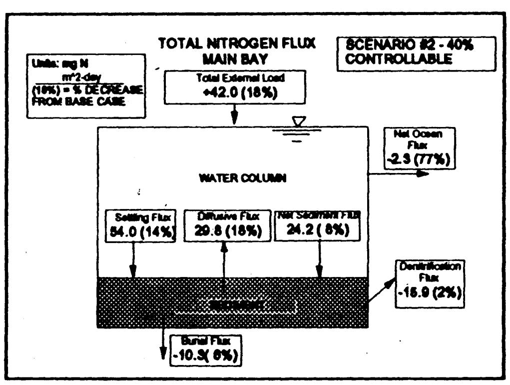
An important consideration in the behavior of nutrients in the Bay is the degree to which nitrogen and/or phosphorus limits phytoplankton growth. One measure of which nutrient is important is the ratio of Dissolved Inorganic Nitrogen (DIN) to Dissolved Inorganic Phosphorus (DIP). Ratios significantly greater than about 7-10 on a mass basis indicate a tendency toward phosphorus limitation while ratios significantly less than that range tend to indicate nitrogen limitation.

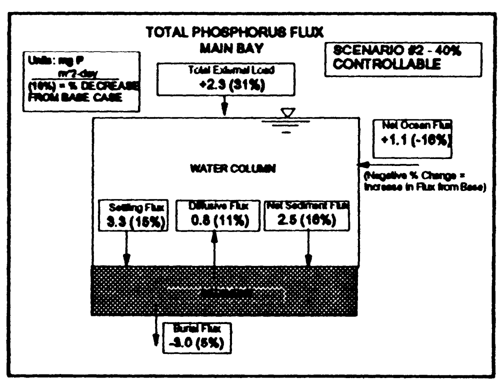


Longitudinal variation of surface DIN/DIP ratio for BASE case. Average over zone over season for average year.

As shown in the accompanying figure, for the base case averaged over zone over the spring, the Bay is calculated to be phosphorus limited from the head to about 75 km from the mouth. During the summer, more of the lower Bay becomes nitrogen limited and during the fall average conditions, more than half of the Bay is nitrogen limited. For the load reduction scenarios, the general tendency is for the LOT N&P and LOT N Only scenarios to increase the region of the Bay that is nitrogen limited. The LOT P Only however, decreases the region of nitrogen limitation because of an apparent increased nitrogen transport to the lower Bay.

Nitrogen and Phosphorus Fluxes The Figures below shows the calculated annual nitrogen and phosphorus fluxes for the main Bay 40% Controllable scenario. Total external load is the load from fall lines, below fall lines, point sources and direct atmospheric deposition to the Bay. Net ocean flux is the net exchange at the mouth of the Bay. The settling flux is the gross settling to the sediment of the Bay. Diffusive flux is the net exchange of dissolved nutrient forms across the sediment-water interface. Net sediment flux is the difference between gross settling and diffusive flux. Denitrification flux is the loss of nitrogen due to the conversion to nitrogen gas, primarily in the sediments. Finally, the burial flux is the net loss of nitrogen or phosphorus from the bottom sediment segment of the model. All fluxes are given in areal units. It should also be noted that these fluxes are for the average year (year #9) of the variable hydrology sequence and

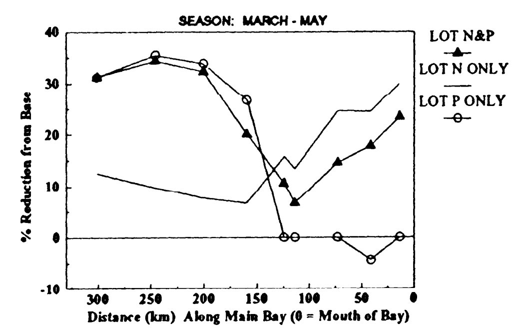




as such reflect a flux "snapshot". It can readily be observed that all fluxes do not necessarily add up to zero because of the dynamic non-steady state nature of the computation.

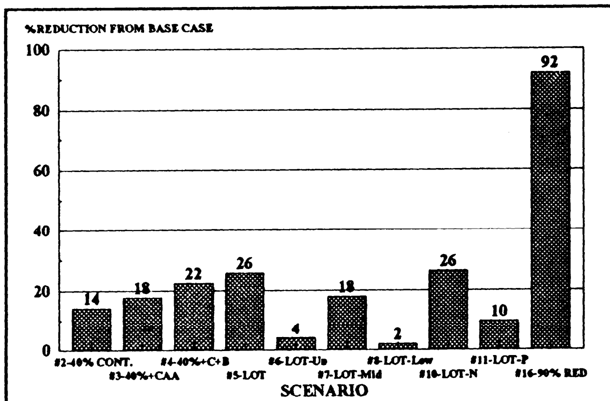
The calculated export of nitrogen and import of phosphorus can be noted. For this scenario, a significant reduction in nitrogen exiting the Bay is estimated while for phosphorus, the influx of phosphorus from the ocean is calculated to increase over the Base case condition. The burial loss of phosphorus is significant and is about equal to the total external load to the Bay.

Phytoplankton Response Several significant insights were obtained by examining the model response of phytoplankton biomass and primary production as a function of nutrient reduction. For the 40% Controllable scenario, phytoplankton biomass is reduced about 10% in the spring (with a minimum percent reduction from Base of zero at about 125 km from the mouth) and about 15% during the summer. As shown in the Figure below, the response of phytoplankton biomass to LOT, LOT-N Only and LOT-P Only reflected the nitrogen - phosphorus limitation regions discussed above. For the spring (similar results occur for the summer), the biomass in the upper 100 km is reduced almost entirely by reductions in phosphorus while the biomass in the lower 100 km is reduced by controlling nitrogen. The increase in percent reduction for LOT- N Only over LOT for both N & P in the lower 100 km is interpreted to result from a down-Bay transport of nitrogen when phytoplankton are reduced in the upper Bay because of control of phosphorus. Because of biomass reduction in the upper Bay by phosphorus control, light penetration is estimated to increase in that region, while for the lower Bay, light penetration will increase because of nitrogen removal.

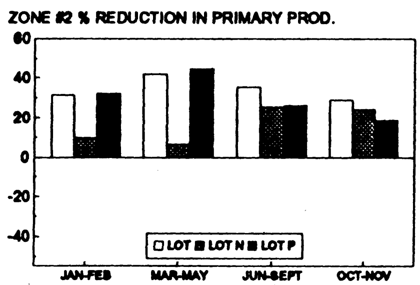


Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

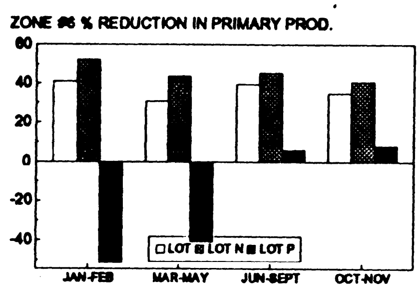
The response in terms of primary production across scenarios is summarized in the next Figure. For the 40 % Controllable scenarios (#2 - #4), it is seen that as the load is increasingly reduced for these scenarios, the impact on the primary production approaches the LOT case. The reductions in the mid Bay areas (LOT-Mid) is also shown to be a significant part of the overall reduction. The annual averages, however tend to mask the actual seasonal dynamics of primary production and the spatial variability of reductions in primary production as a function of which nutrient is reduced. Thus, the LOT P Only annual average reduction is only 10% whereas the spring reduction is over 40%. The responses for two



Reductions in Primary Production for Selected Scenarios. Average Year zones over season and for the three LOT scenarios helps explain these results and are shown in the following two Figures. For Zone 2, the reduction is controlled entirely by phosphorus in the winter and spring whereas in the summer, the production is controlled equally by nitrogen and



Variation of % reduction from Base of phytoplankton primary production. Zone #2. Average over zone over season for average year.

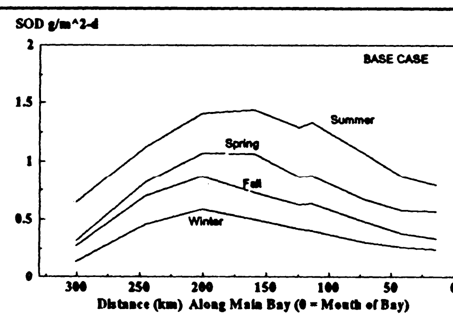


Variation of % reduction from Base of phytoplankton primary production. Zone #6. Average over zone over season for average year.

phosphorus. In the fall, nitrogen is more controlling than phosphorus. For the mid-Bay Zone 4 (not shown), phosphorus controls in the winter and spring whereas nitrogen is the controlling nutrient for the other two seasons. For the summer in Zone 4, LOT P Only results in virtually no change in production over Base case. For Zone 6, the impact of downstream transport of nitrogen to the nitrogen poor regions of the Bay is immediately apparent. For the winter and spring seasons, LOT P Only results in an increase in production over Base case due to this down Bay transport of nitrogen. In the summer and fall, this effect is less pronounced because of the relatively lesser impact of phosphorus reductions in the upper Bay regions during these periods.

These results from the LOT scenarios provide further evidence of the calculated down Bay transport of nitrogen by LOT phosphorus load reduction. Such increases in nitrogen increase primary production in the lower nitrogen limited regions of the Bay and as will be discussed shortly, have a proportionally smaller impact on the DO of the bottom waters of the Bay. On the other hand, phosphorus load reductions have a positive impact in the upper Bay zones where the system is phosphorus limited.

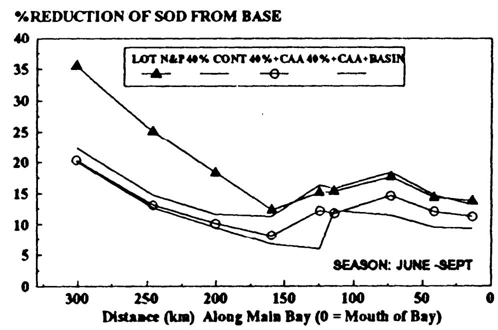
<u>Sediment Oxygen Demand Response</u> The demand of the sediment for oxygen is calculated by the sediment sub-model of the CBWQM. The water column is coupled to the sediment model through the settling of particulate nutrients. The sediment oxygen demand (SOD) is calculated using the net carbon flux to the sediment as the primary input loading. Maximum loading of carbon to the sediment is during the summer months and is the highest in the upper Bay zones. Peak values in this region are about 0.8 gC/m^2-d. The Figure shows the variation in the SOD for the Base case across the zones and for the four seasons. Maximum SOD is calculated to occur in the summer and in Zones 3 to 6. This is in contrast to the carbon flux to the sediment which is maximum in the upper



Longitudinal variation of sediment oxygen demand for BASE case. Average over zone over season for average year.

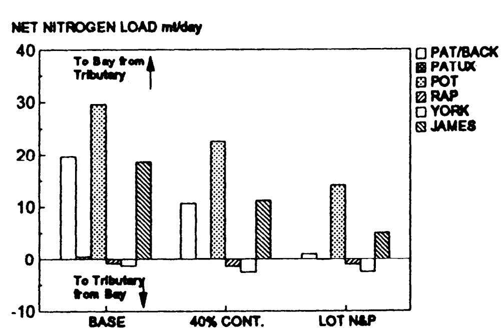
during which there is zero SOD thereby lowering the overall average. On the other hand, the difference may be related to the labile and refractory components of the carbon used in the model. The fall line particulate loadings are considered to be all refractory while the point sources are assumed to be 70% labile and particulate carbon produced from phytoplankton is assumed to be 55% labile. Thus, while the sediment of the upper zones receive more carbon, the nature of the carbon is largely refractory in contrast to the middle and lower zones where the carbon results from primary production and is considerably more labile. Since the calculated diagenesis rate in Zones 3 and 4 is higher than in Zone 2, one concludes that the variable carbon fractions has an effect on the SOD in Zone 2 and together with the periods of zero DO is contributing to the lower calculated SOD in that Zone.

The percent reductions in SOD for the 40% Controllable scenarios (#2 - #4) in comparison to the LOT N&P scenario is displayed in the Figure to the right. The upper Bay reductions in SOD are higher under this latter scenario due presumably to the higher degree of phosphorus removal in the LOT than in the 40% controllable. The differences in nitrogen loading are not as great. For the middle and lower regions of the Bay, the 40% controllable scenarios approach the LOT N&P loading in reducing SOD. In fact, the 40% + CAA + Basin control is at the LOT level of reduction for zones 4 through the rest of the Bay.



Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.

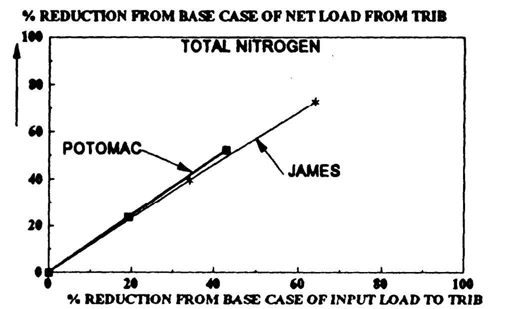
Tidal Tributary Interface Nutrient Loading The net input of the tidal tributaries to the main Bay is of particular interest since such loadings represent actual contributions to the Bay proper. As part of the Bay model calculations, mass balances were conducted around the principal tributaries and the exchange of load across the interfaces of the tributaries was calculated for each of the scenarios.



Variation of annual net nitrogen load from tributaries for Base, 40% controllable and LOT N & P scenarios. Average year.

The net flux of nitrogen across the interfaces of the major tidal tributaries is indicated in the Figure. The three largest inputs are the Patapsco/Back, Potomac and James estuaries. The Patuxent contributes a small input, while the remaining two lower Bay tributaries receive a net input from the Bay. An interesting point of these runs is that the Rappahannock and York rivers are calculated to receive nitrogen from the Bay as opposed to these tributaries providing nitrogen to the Bay. Indeed, under several removal programs (including the 40% Cont. and LOT N&P that are shown) the input net nitrogen load increases from the Bay to the tributary. This is undoubtedly a result of a complex interaction of transport and nutrient concentration where the gradient from the Bay to these tributaries is increased under various removal programs. A similar behavior is calculated for the net phosphorus loadings from the tributaries.

An important linearity in the net interfacial load of both TN and TP from the Potomac and James over the range of loadings from the base to the LOT (not including the geographical runs) is shown in the Figure to the left. As seen for TN , if the total input load of TN to the Potomac or James is reduced by, say, 30% from the base case load, then the net load of TN exiting from the Potomac or James is reduced about 35% from the base case net load. Therefore, in spite of the rather complex nonlinear interactions that exist in the overall model framework, and the apparent interactions between the Bay and the tributaries, the relationship of net load from these two tributaries to the Bay is directly proportional to the reduction in external load to the tributary. However, as noted previously, loads from the James influence only the lower Bay and mouth region, while load reductions from the middle Bay including the Potomac provide significant improvements in the main Bay water quality.



Relationship between % reduction of input load to tributary and net load exiting tributary to Bay for TN.

The ability to examine the behavior of the Bay with the calibrated CBWQM under different removal levels of nutrients in combination is a particularly important use of the model. Such behavior is not directly observable in the Bay and can only be predicted by a credible model. The degree to which phosphorus and nitrogen load reductions have an impact on the water quality of the Bay is of course an important consideration in the decision making process.

In general, the Bay can be divided into three broad regions: the upper approximately 100 km of the Bay where control of phytoplankton growth is by phosphorus, the approximately 100 km of the lower Bay where the phytoplankton production is controlled by nitrogen and a middle Bay region of about 100 km where a transition takes place. The extent of nitrogen control proceeds up the estuary during the summer and fall and is a function of fresh water hydrology and resulting circulation. This general conclusion is consistent with interpretations of observations made on the Bay by a variety of investigators. Modeling shows that as phosphorus loadings to the Bay are reduced (with nitrogen loadings remaining at approximately Base levels), excess nitrogen is transported down the Bay in the surface waters. This transported nitrogen then stimulates phytoplankton production in this nitrogen limited region of the Bay. This "additional" relatively labile biomass then settles in the downstream region and contributes to higher SOD in that area. Phosphorus removal however has a distinctly positive effect in the surface waters of the upper Bay where spring and summer phytoplankton biomass are reduced considerably more than if only nitrogen were removed. Such reductions of biomass of 20-30% have an impact on light penetration, with a 20% increase in light calculated for the 2 m depth at LOT levels.

Reductions in nitrogen have of course a direct effect on phytoplankton production in the nitrogen limited areas and subsequently on the carbon fluxes and the SOD. In addition, the nitrogen load reductions result in improvement in meeting the DIN habitat requirements for the SAV.

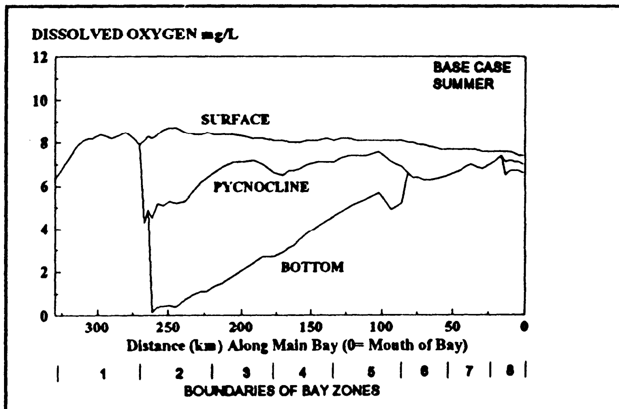
It is concluded from the analyses reviewed here, that load reductions of both phosphorus and nitrogen are necessary to result in reductions in the nutrients, phytoplankton biomass, (with increases in light penetration) and sediment oxygen demand. Phosphorus load reductions are most effective in achieving improvement in these measures of water quality in the upper Bay. Nitrogen removal is required throughout the Bay: in the upper Bay to reduce nitrogen loads that would be transported down Bay under the phosphorus reduction and in the middle and lower Bay to directly reduce biomass and hence SOD.

The Susquehanna River, a non-tidal tributary to the Bay accounts for a majority of the nutrient input on an average annual basis (about 42% of the TN and 31% of the TP loads). The net input of nutrients on an annual average basis from the principal tidal tributaries to the Bay is exclusively from the Patapsco/Back, Potomac and James estuaries. The Rappahannock and York estuaries are calculated to receive a net input of nitrogen and phosphorus from the Bay. For the Potomac and James estuaries, the net nutrient load exiting the tributary to the Bay is approximately linear to the external load of nutrient to the tributary. Nutrient loads from the Potomac enter the middle Bay region where water quality impacts persist while nutrient impacts from the James are limited to the lower Bay and Bay mouth region.

DISSOLVED OXYGEN RESPONSE

The calculated response of the dissolved oxygen (DO) of the Bay assumes particular importance in analyzing the effects of scenario nutrient load reductions. The dissolved oxygen focus in this Section is twofold: (1) evaluation of the seasonal (specifically summer) average DO response, and (2) analysis of the response of the DO concentrations below 1 mg/L, the working definition of anoxia. The latter quantity is determined by calculating the volumetric extent and temporal extent of DO below 1 mg/L. These "anoxic volume-days" have units of m^3 - days.

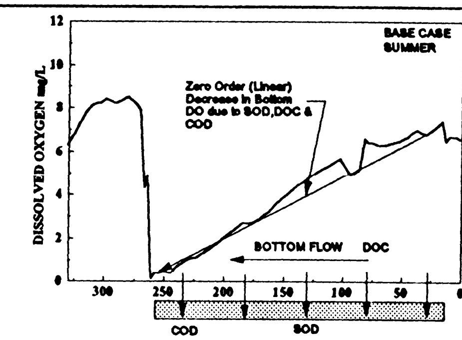
The summer average longitudinal DO profile for the Base case loading condition and for the average hydrology flow year is shown here. The summer profile is the basis for comparison of assessing the effect of nutrient reduction scenarios. The rapid drop of the minimum bottom DO between the spring level of greater than 5 mg/L to the minimum summer average level of 0.1 mg/l can be noted. The steep increase in the bottom DO beyond the upper limit of the deep trench at approximately 260 km is due to a rapid decrease in depth. The marked vertical gradient in DO during the summer can also be seen where average



Calculated longitudinal variation of DO for Base case averaged over SUMMER for average year.

surface DO is generally supersaturated due to algal productivity and the bottom DO is responding to deep water sinks of oxygen. The marked difference in the longitudinal profiles between the surface and pycnocline levels and the bottom level can also be noted. Examination of the bottom DO longitudinal summer profile indicates an approximate linear decrease in DO as one progresses up the Bay. A simple analysis of the behavior of the DO in the bottom waters can be made to help understand this behavior.

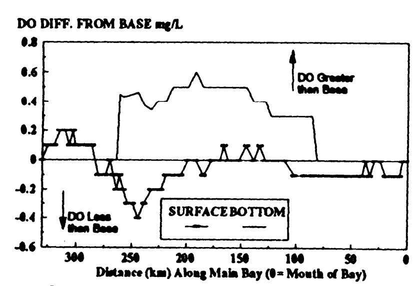
The principal sinks of oxygen in the bottom water are the sediment oxygen demand (SOD), the oxidation of the dissolved organic carbon (DOC) and the immediate uptake of oxygen to satisfy the chemical oxygen demand (COD) of reduced substances released from the sediment. Phytoplankton respiration is neglected since during the summer the bottom layer phytoplankton biomass is small. In the CBWQM, the sediment and water column are interactive and not separated. However, since the output from the sediment model is computed as equivalent SOD and COD, an analysis can be made considering these processes as external sinks of DO. The rates of utilization of oxygen in the model are oxygen dependent, but this complication is not considered here in this simple analysis. Also, vertical mixing of oxygen is not included which simplifies the analysis considerably. The DO concentration is thus given by a linear equation



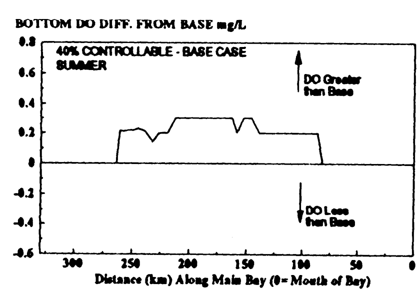
Showing approximate zero order (linear) decrease in bottom DO, Base case, Summer, average year.

The accompanying Figure illustrates this behavior. At the head end of the trench after the approximately 17 days of total travel time, the total DO decline is then about 6.5 mg/L or for an initial bottom DO at the mouth of the Bay of about 7 mg/L, a DO of about 0. 5 mg/L is calculated. The analysis represents a general process of bottom water moving up the Bay, losing oxygen during the time of travel of the parcel (due principally to a constant withdrawal of oxygen to satisfy the SOD) and arriving at the head end of the trench at anoxic levels.

The Figures below show the summer average DO for the LOT N&P and the 40% Controllable scenarios. For the LOT N&P, the bottom DO is improved, but not to the point of raising the DO above anoxia (i.e., DO < 1 mg/L) on a summer average basis. Analysis of the



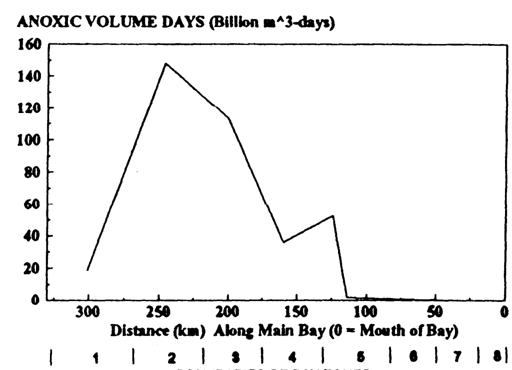
Longitudinal variation of DO difference between LOT and Base case averaged over summer for average year.



Longitudinal variation of bottom DO difference between 40% Controllable scenario and Base case averaged over summer for average year.

range of load reduction indicates that only when the incoming loads are reduced by at least 50% of the external load is the summer average bottom DO calculated to be greater than 1.0 mg/L. The 40% controllable scenario improves the bottom DO by about a constant 0.2 mg/L on a summer average basis which is about half of the LOT N&P scenario.

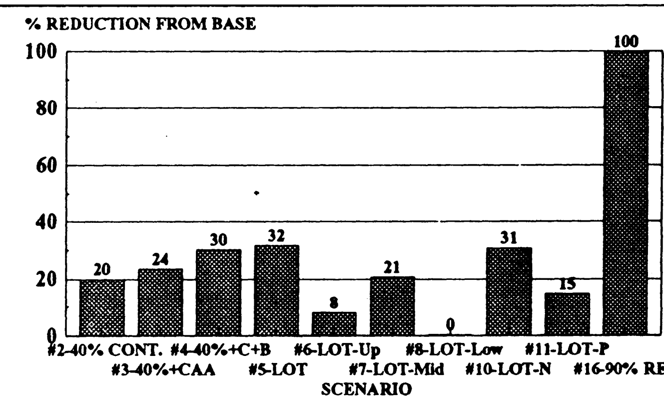
Anoxic Volume Days Response As noted above, a useful measure of the degree of anoxia is the total volume •days where the DO was calculated to be less than 1 mg/L. That is, anoxia is tracked on a volume basis over time and a sum is tabulated for each scenario. Maximum anoxia occurs in the summer with about 16% occurring in the spring and fall and none in the winter. The longitudinal variation of the anoxia as shown to the left indicates peak regions in zones 2 and 3 where about 70% of the annual total occurs. An additional 24% occurs in Zones 4 and 9 (Eastern Shore).



Longitudinal variation of anoxic volume days for Base case total over zone for average year.

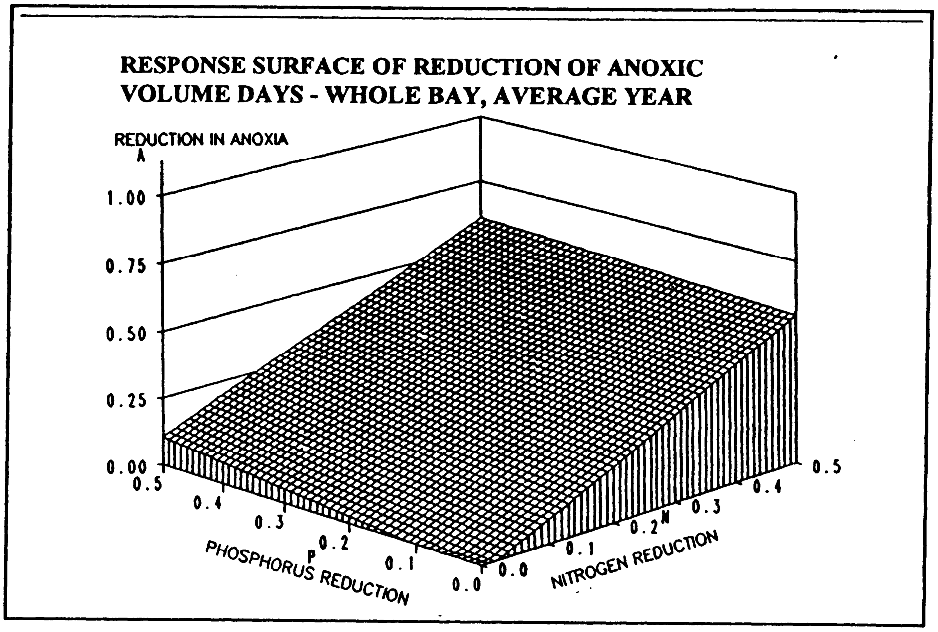
The percent reductions in total annual anoxic volume days from the Base case for selected scenarios is shown below. Complete elimination occurs at 90% N&P removal (Scenario #16). The upper limit of anoxia reduction provided by the best technology (LOT) is about 30%. Note that 40% controllable +CAA+Basin control (Scenario #4) approaches the improvement from LOT N&P (#5).

The relative impact of nitrogen and phosphorus is seen by comparing #10 and #11 with



Percent reductions in anoxic - volume - days from Base case for selected scenarios. Average Year

#5. As noted above, LOT P Only has less of an impact on the bottom DO and as shown in Figure VII - 12, only a 15% improvement in anoxia is calculated which is half that from LOT N Only. The relationship between nitrogen and phosphorus loadings and the response in terms of anoxic volume •days is further described by the use of response surface analysis. Combining scenario runs in a single plot of Bay wide anoxia reduction versus TN and TP load reductions allows the visualization of the change in DO improvement as a function of nutrient reductions. Such a surface is shown below.



As seen from this Figure, reductions in TN improve the DO conditions more than reductions of TP of the same magnitude. It should also be noted that LOT N Only has a greater reduction in primary production during the summer months in the mid to lower Bay regions. Since maximum anoxia occurs during the summer, LOT N Only can be expected to also have a relatively larger impact on summer anoxia than LOT P Only.

In addition to this hypothesized effect, two other effects may also contribute to the reduced effect on anoxic volume-day response to the LOT - P Only scenario. As noted previously, reduced phosphorus loading reduces primary production in the surface waters of the upper Bay. Such a reduction has the following two consequences:

(1) the reduced algal growth at the surface decreases surface water DO which in turn decreases the vertical concentration gradient thereby reducing the exchange of DO and replenishment of bottom DO in the upper Bay, and

(2) the reduced algal growth will not assimilate as much ammonium with the result that nitrification will increase in the surface waters, decreasing the DO and again decreasing the vertical transport of oxygen to bottom waters of the upper Bay.

It can also be noted that the location of where LOT load reductions are applied is also significant. Thus, comparing Scenarios #6,#7 and #8 indicates that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. That is, as Figure VII - 12 indicates, there is a negligible percent reduction in anoxic volume days under Scenario #8 (LOT - Lower Bay) as compared to 8% for Scenario #6 (LOT - Upper Bay) and 21% for Scenario #7 (LOT - Middle Bay). The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no net input of nutrients from the Rappahannock and York estuaries (but an input from the

Bay into these tributaries), and (b) transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

<u>Conclusions</u> The results presented in this Section indicate the following:

1. Bottom DO concentrations under Base case conditions reach minimum summer average levels of less than 1 mg/L. The approximate linear decline in oxygen with distance as one proceeds up the Bay in the direction of the bottom flows is a result of the distributed sink of oxygen occasioned principally by the sediment oxygen demand. As such, the minimum bottom DO at the head end of the trench reflects the accumulated DO depletion of a bottom water parcel since it entered the Bay. All SOD along the path of bottom water contributes to the DO depletion.

2. Feasible reductions in nutrient loadings of about 20 -30% N & P (i.e., LOT and "40% controllable" scenarios) result in improvement in bottom DO over Base by about 0.2 - 0.4 mg/L as a summer average.

3. Load reductions of about 50% or greater result in minimum summer average DO concentrations above 1 mg/L.

4. 90% N & P reductions are calculated after the ten year simulation to result in average summer DO of greater than 5 mg/L.

5. A measure of anoxia as given by the volumetric and temporal extent of DO less than 1 mg/L (the anoxic volume days) is a maximum in the summer and in Zones 2-4 under Base case. The feasible load reduction scenarios result in a range of reduction in anoxic volume days of about 20 - 30% from Base. This reduction in anoxia is directly proportional to the load reduction of nitrogen of about 20-30%.

6. Response surface analysis of anoxic volume days on a Bay wide basis indicates a generally linear response in anoxia reduction as a function of nitrogen with little effect due to phosphorus reductions. The maximum effect of phosphorus is in Zone 4, a region that contributes a relatively smaller fraction to the Bay wide total anoxia.

7. Even though the upper Bay is phosphorus limited, reductions of phosphorus do not have as significant an effect on anoxic volume days as do nitrogen reductions. The reasons for this response are complex . Phosphorus controls primary production in the winter and spring while nitrogen controls primary production in the summer, the period of maximum anoxia. Also, when only phosphorus is removed there is a calculated increased nitrogen transport to down Bay nitrogen limited regions which increased downstream SOD. This effect is apparently coupled with reduced primary production in the surface waters of the upper Bay resulting in a reduced vertical DO gradient and less oxygen transferred to the bottom waters of the upper Bay.

8. The location of where LOT load reductions are applied is also significant. Thus, the scenarios where LOT reduction were selectively applied by Bay regions (Upper, Mid and Lower) indicate that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. A negligible percent reduction in anoxic volume days is calculated for LOT in the Lower Bay only as compared to 8% for LOT for the Upper Bay and 21% for LOT in the Middle Bay. The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no annual net input of nutrients from the Rappahannock and York estuaries (but rather an input from the Bay into these tributaries) and (b) possible transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

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